Dynamic behaviour of liquid droplets bouncing onto a hot slab

F. Lelong*,†, M. Gradeck†, N. Seiler*,1, P. Ruyer*, G. Castanet† and P. Dunand†
* IRSN/DPAM/SEMCA/LEMAR, Cadarache Bâtiment 700, BP3
13 115 Saint Paul lez Durance cedex
† LEMTA Nancy-University CNRS, 2 avenue de la forêt de Haye, BP160
54504 Vandoeuvre cedex

Abstract
A liquid droplet stream impinging a surface (T~500-600°C) in the Leidenfrost regime has been studied. In this particular regime, a thin vapour layer appears between the droplets and the slab so that direct contact with the solid is avoided. This vapour layer insulates the droplet from the solid surface, minimizes the loss of energy at the impact and so permits the rebound of the drop. In this paper, we propose an analytical approach based on a spring's analogy in order to estimate the resident time of a drop impinging a hot surface, the maximum spreading diameter of the drop during the impact and its evolution. Finally, the results are compared to experimental data.

Introduction

In a pressurized water reactor (PWR), during a Loss Of Coolant Accident (LOCA), the fuel assemblies are not cooled anymore by the surrounding liquid water; the temperature rises to such an extent that some parts of the fuel assemblies can be deformed resulting in "ballooned regions". When reflooding occurs, the cooling of theses partially blocked parts of the fuel assemblies will depend on the coolant flow characteristics involving overheated vapour and droplets. So far, most of the existing models for heat transfers have been focused on the cooling of ballooned regions by vapor convection. However a two-phase mist flow exists (ie a post dry-out dispersed flow regime), the possibility of additional cooling by direct liquid droplet impingement on the blockage surfaces must be investigated. Preliminary studies about LOCA reveals that the droplet diameter is expected to be in the range of 10mm-1mm, and their velocity less than 10 m/s, while the wall temperature is above 600°C which is much higher than the Leidenfrost temperature of liquid water. Under such conditions, the impact regimes are predominantly the bouncing and the splashing regimes. The experiments are performed on very small droplets (about 100 µm) injected periodically using a monodisperse generator that allows to control separetly the droplet frequency, velocity, size and velocity at the injection. The wall is a very thin disk of nickel (D_{Ni}=25mm, e_{Ni}=500mm) heated around 600°C by an electromagnetic set-up. For 100µm-sized droplets, the droplet/wall interaction is very short (a few of ms), a high-speed camera is therefore required to visualize the impingement process. The images are processed in order to measure the droplet incident angle and velocity, as well as their resident time and spreading diameter.

The final goal of this study is the estimation and modelization of the heat flux removed at the wall by impinging droplets (front face of the disk) ; the heat flux is estimated by coupling the temperature field (measured in the rear face of the disk using a fast infrared camera) to a semi-analytical inverse heat conduction model [1].

Modeling the liquid droplet's impact

The energy transferred to a spherical drop (Q) can be modeled as the integral over the residence time (t_R) of the drop on the wall, of a conductive heat flux between wall and drop bottom interface through the vapour cushion thickness (δ_V):

$$Q = \int_0^{t_R} \dot{Q} dt \quad \text{with} \quad \dot{Q} = \frac{\lambda_V \left[T_w - T_{sat}\right] \pi R^2(t)}{\delta_V} \tag{1}$$

The modeling of the energy transfered from the wall to the droplet, equation (1), requires modeling of the vapour thickness, δ_V, the radius of the spreading drop, $R(t)$, and its residence time, t_R.

[1] Corresponding author: nathalie.seiler@irsn.fr

The thickness of the vapour cushion can be estimated from momentum and energy equations in the lubrification theory framework. Detailed derivation is given in the extended paper. Finally, the vapour thickness can be expressed as:

$$\delta_V(t) = \frac{D(t)}{D_0}\left(\frac{9\mu_V \lambda_V \left[T_w - T_{sat}\right] D_0}{16\Delta h_{LV}\rho_V \rho_L g}\right)^{0.25} \tag{2}$$

It shows that the evolution of the vapour thickness is directly linked to the dynamics of the spreading diameter, *D(t)*. To evaluate analytically this parameter during the droplet impact, analogy with a mass/spring is performed.

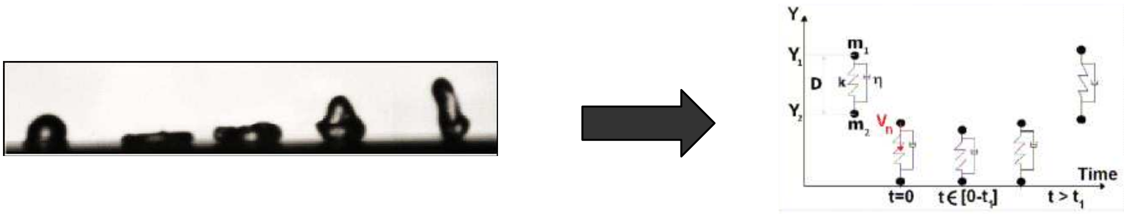

Figure 1. description of the analogy between the drop and the mass/spring system

In this approach, the mass of the liquid droplet is splitted into two equal masses, m_1 and m_2, separated by a spring system (stiffness *k* and viscous damping constant η). Newton's equation applied to the mass m_1 describes the movement of the spring when it deforms:

$$m_1\frac{\partial^2 Y_1}{\partial t^2} + \eta\left(\frac{\partial Y_1}{\partial t} - \frac{\partial Y_2}{\partial t}\right) + k\left(Y_1 - Y_2 - D_0\right) = -m_1 g \tag{3}$$

This analogy has been already used by [2] [3] to describe the rebound of liquid drop but in the case where stiffness could be assumed as a constant. It is no more valid in our case since stiffness is a function of the surface energy [4] therefore the droplet surface. Stiffness is evaluated assuming that it is deforming like an oblate spheroid while viscous damping is estimated through a dimensional analysis. Assuming Y2=0 as the drop impacts the wall, the previous equation led to the estimation of the residence time.

The whole model has been validated for 7 different liquids (water, acetone , ethanol, heptane, hexanol, isopropanol, decane) on tests for different Weber number. The model can accurately assess the dynamics the spreading of a droplet impacting on a hot wall. Indeed, the maximum spreading diameter is well estimated by the model for the 7 fluids studied.

We shown in particular that the model well capture the dependency of the dynamics with the weber number and that this dynamics can only be explained when viscous dissipation inside the droplet is taken into account.

References

[1] Lelong F., Gradeck M., Remy B., Ouattara A. and Maillet D., *Inverse conduction technique in Hankel domain using intrared thermography: application to droplet stream quenching a metal disk*, to be presented in next IHTC14, August 2010, Washington

[2] Clanet C., Beguin C., Richard D., Quéré D., *Maximal deformation of an impacting drop*, J. Fluid Mech, 517, 199-208, 2004.

[3] A.L. Biance, F. Chevy, C. Clanet, G. Lagudeau, D. Quéré, *On the elasticity of an inertial liquid shock*, J. Fluid Mech, 554, 47-66, 2006.

[4] Lord Rayleigh, 1897, *On the capillary phenomena of jet*, Proc. of the Royal Society of London, 29, 71-97